Bees, coffee, and poverty: How alternative policy instruments and ownership structures affect technology choice?

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Abstract

We investigate what role economic instruments can play in preserving biodiversity in developing countries, or in agroforestry management in coffee production, in particular. Most coffee producers live in poverty and manage agro-ecosystems in some of the world's most culturally and biologically diverse regions. What makes coffee farming an interesting case for biodiversity is the relatively recent finding that bees can augment pollination and boost coffee crop yields substantially. Despite the proved positive impacts of biodiversity on production in the long run, short term revenues from intense monoculture drive land use decisions. Our study investigates the possibility of multiple equilibria in adoption of technology (sun and shade grown coffee): all farmers adopt environmentally detrimental farming practices, or all farmers adopt sustainable practices, or both farming practices co-exist. We calibrate an empirical model to examine under what circumstances the multiplicity actually occurs. We then characterize the equilibria and carry out comparative statics analysis to investigate the impacts of alternative policy measures.

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1 Introduction

The value of ecosystem services of pollinators for commercial agriculture and to the global ecosystem is widely recognized (see, e.g., Siebert, 1980, Olmstead and Wooten, 1987, Daily, 1997, Ricketts et al., 2004). The dilemma for management is that the benefits of biodiversity conservation accrue to the local and global community at large, but the short term costs are borne solely by the local community. A typical example is farming practices of cash crops based on intense monoculture with high short-term returns, but potentially dramatic losses in yields in the long run due to decreased biodiversity and pollinator declines. (Kevan and Phillips, 2001, Nunes et al., 2003) Yet, biodiversity conservation is rarely a major feature in international aid agreements to alleviate poverty. (EU, 2005)

We investigate what role economic instruments can play in developing countries in preserving biodiversity when simultaneously aiming at eradication of poverty. We incorporate scientific ecological findings on the role of pollination services into an economic analysis on agroforestry in coffee production. Coffee is one of the most significant products in world trade, exports reaching 7 billion dollars in 2004. It ranks as one of the five most valuable export commodities and employs about 25 million people worldwide (FAOSTAT, 2005, Ricketts et al., 2004). Over 70% of the world's coffee is produced by small-scale family farms. Most coffee producers live in poverty and manage agro-ecosystems in some of the world's most culturally and biologically diverse regions in Latin American, Asian, and African countries. Despite the increasing evidence that the abundance and diversity of bees can augment pollination and boost coffee crop yields in the long run (Oxfam, 2001, Roubik, 2002, Klein et al., 2003a,b,c), shadow trees on plantations and forest fragments nearby coffee farms are removed for the sake of greater short-term efficiency. The resulting loss of pollinator habitat is a substantial environmental problem worldwide (Kremen and Ricketts, 2000). Moreover, due to overproduction caused by, for instance, rapid expansion in Vietnam and Brazil and more technologically oriented production in Colombia and Costa Rica, international coffee prices have fallen substantially and are at their lowest levels for decades. (Lewin et al., 2004, Perfecto et al., 2005) This worsens the situation of poor farmers and provokes the destruction of the forest strips.

A few recent studies have paid attention to economic value of pollination services materialized through agroforestry benefits in coffee production systems, see, e.g., Ricketts et al. (2004). Gobbi (2000) finds that investment in biodiversity-friendly certification criteria is financially viable for coffee farms, while Benítez et al. (2006), Ninan and Sathyaplan (2005), and Olschewski et al. (2006) note that the high opportunity costs of land managed by ecological principles, in terms of lost benefits of intensely cultivated coffee or alternative crops, spurs biodiversity degradation. An overall conclusion from these studies focusing on the value of pollination services is that policy measures such as trade-related standards, premiums, tax relieves, or government institutions are necessary for adoption of biodiversity-friendly growing practices (see also Damodaran, 2002, Bacon, 2005, Perfecto et al., 2005).

Another strand of related literature has to a certain extent considered alternative policy instruments for protecting the endangered natural ecosystems. There is a certain appealing evidence that direct methods such as conservation payments are more cost-efficient than indirect methods such as output and investment subsidies, when policy programs target at large increments in conservation areas. See, e.g., Ferraro and Simpson (2002), Ferraro et al. (2005). Interestingly, the empirical results of these case studies on apiculture in Madagascar may in fact hint at a possible reason for the popularity of indirect methods compared to the direct ones: the income in the recipient, low-income nations is increased considerably already with a small incremental increase in the protection of rain forests. Increased income is often the most important goal in many projects motivated by long term sustainability and eradication of poverty (for an ongoing debate on this issue, see, e.g., Ferraro and Kiss 2002, Swart 2003). This aspect has not been considered explicitly in biodiversity studies. We ask whether the performance of alternative economic instruments is affected if there are two simultaneous goals, protection of biodiversity and abolition of poverty.

To get insight into mechanisms that drive the land allocation processes, the choice between environmentally detrimental and sustainable farming technology is determined in our model by relative profits of the alternative technologies (cf. e.g. (Bulte and Horan, 2003)). We augment the previous policy analyses by modeling explicitly ecosystem services provided by pollinators. Our study investigates the possibility of multiple equilibria in adoption of technology: all farmers adopt environmentally detrimental farming practices, or all farmers adopt sustainable practices, or both farming practices co-exist. We characterize the alternative equilibria and calibrate an empirical model to describe land use decisions at a representative local community level, and examine under what circumstances the multiplicity actually occurs.

Furthermore, we investigate three alternative policy tools 1) price premiums for fair trade/eco-labeling, 2) conservation payments, and 3) minimum wages. All instruments can be used for reducing environmental impoverishment, but they work differently. Fair trade certification is an example of market-based conservation strategy. Consumers can promote biodiversity by paying a premium price for coffee which is produced on certified farms committed to preservation of biodiversity (see, e.g., Perfecto et al., 2005, Swallow and Sedjo, 2000, Sedjo and Swallow, 2002). Conservation payments are an example of targeted aid which is typically used for establishing protection areas (see, e.g., Ferraro and Simpson, 2002). A minimum wage represents a policy instrument designed for reducing inequality and preventing rural outmigration in developing countries (Bhagwati and Srinivasan, 1974, Basu, 1980, Lustig and McLeod, 1977, Gindling and Terrell, 2005, Lall et al., 2006). Our concern is that instruments aimed primarily for abolition of poverty (such as minimum wages) and, on the other hand, for protection of biodiversity (price premiums for eco-labeled products and conservation payments) are likely to have conflicting outcomes when input use intensity or production cost structure of alternative technologies differ. We carry out comparative statics analysis to investigate the impacts of alternative policy measures.

Our study contributes to the previous literature by approaching the valuation of pollination services from a new angle. We recognize that maintaining environmentally sustainable farming practices requires ”over-allocation” to this technology compared to what would be economically optimal. This inefficiency is inevitable and results from inability to coordinate management decisions when there are several economic agents such as small-scale farmers involved. When designing conservation policies, the cost of conservation can be measured in terms of inefficiency resulting from forsaking profit maximizing technology for the (option) value of biodiversity preserved using the environmentally sustainable technology. Moreover, our results indicate that if policies for promoting on the one hand ecological and, on the other hand, economic (social) sustainability are designed independently, the policy instruments may in fact counteract each other’s impacts.

The rest of the paper is organized as follows. In Section 2 we discuss the basic background concepts of this paper, namely coffee production and its relation to pollination and biodiversity. In Section 3 an analytic model is presented, and the model is applied to a specific case in Section 4. Finally, Section 5 provides some conclusions.

2 Coffee production, pollination and biodiversity

In this section, we review the basic characteristics of coffee production, its relation to insect pollination, and the characteristics of the two production technologies discussed in this study. The discussion is by no means complete. Instead we concentrate on aspects that are relevant from the point of view of our analytic model and the empirical application. The main issues to be considered are that coffee can be produced using two alternative production methods, and the biodiversity and economic profitability implications of the production methods differ crucially from each other.

2.1 Coffee plants and pollination

About two thirds of world's crop species include cultivars that require animal pollination and approximately one third of food consumption in tropical countries originates from plants that are insect pollinated (Kremen et al., 2002, Ricketts et al., 2004). Two main coffee variants are used in production. *Coffea canephora* var. *robusta* is grown mainly in West Africa and Southeast Asia and *Coffea arabica* mainly in South and Central America, although this geographical division has begun to disintegrate (Dicum and Luttinger, 1999).

The highland coffee plant (*C. arabica*) is self-pollinating, but it has been shown that cross-pollination by insects may increase the fruit set[1] in sites far from the nearest forest. The lowland coffee plant (*C. canephora*) is self-sterile and predominantly wind-pollinated, but also it has been shown to produce higher fruit set in plants that were pollinated by both wind and insects as opposed to just wind. In addition, cross-pollination is likely to lead to larger and more robust fruit, hence increasing both the quality and the quantity of the crop. (Klein et al., 2003a,b,c, Ricketts et al., 2004, Roubik, 2002).

It has recently been shown that it is both the diversity and the abundance of bees that are important for pollination. Hence, biological diversity provides greater and more predictable pollination services and increases the fruit set (and hence yield) of coffee plants. Predictably, bee diversity and abundance decrease with the distance to the nearest forest. As a result, the fruit set (and hence yield) of the open pollinated coffee plant is reversely correlated with the forest distance. In order to maintain the pollination service provided by the wild bee populations to coffee plants, the forest habitat of the bees needs to be conserved. (Klein et al., 2003b,c, Kremen et al., 2002, Ricketts et al., 2004, Steffan-Dewenter and Tscharntke, 1999)

2.2 Coffee markets and production

Demand for coffee has been fairly stable over the past years. However, demand for certified fair trade and organic gourmet coffee has been growing fast, especially in the United States and the European Union, although their market share is still very small[2] (Bacon, 2005). On the other hand, supply fluctuates substantially, primarily due to weather conditions. This variation is exacer-

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[1] Fruit set is the number of fruits at harvest divided by the original number of flowers (Ricketts et al., 2004).

[2] In 2003, the Netherlands and the US were the largest destinations for fair trade coffee by importing about 8500 tons each, with fair trade market shares of about 3.5% and 1% of all coffee, respectively. (TransFair USA, 2005)

bated by the fact that coffee takes about three years from planting to harvest (one and a half years for hybrid variants), and thus the harvest area cannot be quickly altered to maintain a stable supply. In addition, coffee has a biannual production cycle, which further limits the possibility to adjust production to the market situation (Agne, 2000, Dicum and Luttinger, 1999). As a result, the average price of coffee has fluctuated substantially — for instance from about \$0.60 per pound in 1992 to about \$1.80 five years later and back to \$0.60 another five years later (Lewin et al., 2004).

The six basic tasks in coffee production include: *i*) pruning of the (possible) shade trees; *ii*) pruning of the coffee bushes; *iii*) fertilization of the coffee bushes (most important external input); *iv*) weed control; *v*) pest and disease management; and *vi*) harvesting (Agne, 2000). Coffee production can be roughly divided into two main methods of production. The traditional method (henceforth 'shade coffee') is to grow coffee in mixture with shade trees that may produce also alternative products of economic value (e.g. fruits, medicine). This method involves relatively fewer coffee plants per hectare, relatively slower growth and smaller yield per plant and lower requirement for commercial inputs. On the other hand, the method imposes positive impacts on biodiversity and soil as well as involves relatively longer plant life-span.

The other method originated from the green revolution, and it is to grow coffee in the open air, without shade (henceforth 'sun coffee'). These plantations are de facto monocultures with intense production. The production method allows more coffee plants per hectare and produces relatively quicker and higher yield per plant. On the other hand, it has negative impacts on biodiversity and soil, involves relatively shorter plant life-span and imposes reliance on a single crop (coffee). Given that sun coffee is intensively produced and generally hand pollinated, whether there are or are not pollinating insects nearby is of little relevance. In contrast, for the shade coffee production the insect pollination service is important. Coffee production thus involves not only economic dimensions but is also important from the environmental point of view. That is why the two production technologies analyzed in this study include different *i*) yield per hectare; *ii*) producer price per kilogram; *iii*) production costs per kilogram; *iv*) production costs per hectare; and *v*) dependence on forests and pollination.[3]

Finally, there are certain aspects in our empirical model that need to be commented. In particular, the shade coffee technology attracts a price pre-

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[3] Our rough division into sun and shade coffee is a simplification of the actual production technologies. For instance Moguel and Toledo (1999) divide coffee production systems in Mexico into five categories: *i*) rustic; *ii*) traditional polyculture; *iii*) commercial polyculture; *iv*) shaded monoculture; and *v*) unshaded monoculture. However, we wish to highlight the differences that are important from the point of view of this study. Thus the division into only two categories in our classification.

mium from the international market, hence giving a higher producer price. On the other hand, shade production involves a higher cost of production per hectare, due to more labor required in production. Additionally, whereas the per hectare yield of sun coffee is assumed constant, the yield of shade coffee depends on the distance to the nearest forest. Thus in our shade coffee system it is not the shade trees that provide the pollination services. Instead, the shade coffee system includes a forest strip located at the edge of the production area. This is justified by the fact that in the area we use to provide parameters for our empirical application (Costa Rica), the decisive matter for pollination is the distance to the nearest forest, not the shade trees (Ricketts et al., 2004).

Ricketts et al. (2004) provide one of the first attempts to estimate the economic value of bee habitat conservation to the coffee producers. Within a single large farm in Costa Rica, they estimated that the forest fragments provide pollination services worth $60,000 annually. In order to provide some structure to our empirical application, we adopt from this study the production area, the forest area, and the yield and forest distance parameters used in calibrating our model. Another economic study that has recently been conducted is that of Olschewski et al. (2006), who analyze the economic impact of pollination on both fruit set and berry weight. In our analysis, we assume the impact of pollination only through increased fruit set, ignoring impacts on berry weight as well as any possible quality improvements.

3 The Model

In this section we first derive the profit functions of sun-coffee and shade-coffee production technologies. Then we investigate two different farm structures: sole ownership and small scale farms. Under sole ownership there is a single decision maker who makes the land allocation decision optimally between sun coffee and shade coffee. In the other setting there are several small farmers in the region and they make decisions between choosing the two technologies. We do not consider how the small farms are actually located and we assume that the shape of the shade coffee region is independent of individual farmers' actions. This makes it possible to formulate a static equilibrium model that does no account for the process that would actually take place when farmers make their technology choice decisions. Rather we describe the economic outcome of such process.

We let A denote the total area of land that is allocated to coffee production. We have two technologies for coffee production: sun coffee and shade coffee, which we index with 1 and 2, respectively. The variable μ denotes the portion of the area that is allocated to shade-coffee production. The portion that is allocated for sun coffee is then $(1-\mu)$.

3.1 Yields and Profits

We assume that the yield of sun coffee depends only on the area which is allocated to its production. This assumption dismisses the effect of pollinators on the yield. The assumption is, however, reasonable since in the sun-coffee production the plants are pollinated manually as discussed earlier. The yield is then simply $(1-\mu)Y_1 A$, where Y_1 is the yield per hectare.

We divide the costs of producing coffee into two categories: costs that depend on the yield, e.g., harvesting and transportation costs (c_1), and costs that depend on the area of production (e_1). Labor costs form the major part of the area dependent costs. If the per unit producer price of sun coffee is p_1 then the profits are

$$\pi_1(\mu) = (p_1 - c_1)(1-\mu)Y_1 A - e_1(1-\mu)A.$$

As for the shade coffee we assume that the yield depends on the pollinators. Klein et al. (2003c) have shown that pollination effects depend on the distance of coffee plant to the border of the pollinator source (the forest). We assume that the coffee plants form a continuous cover over the region in which they are grown; each point of the region produces some coffee.

Let x be the location of a point in the shade coffee region and $d(x)$ its distance to pollinator source. We assume that the relationship between the distance and yield at the point is given by $\alpha - \beta\sqrt{d(x)}$ with the exception that the yield cannot fall below a certain minimum level $y_{\min}$. Hence, the yield at x is $y(x) = \max\{y_{\min}, \alpha - \beta\sqrt{d(x)}\}$. This model is based on the results of Klein et al. (2003c), who have estimated the similar square-root relationship between the initial fruit-set of a plant and the distance to forest. Assuming that the yield is proportional to the initial fruit-set we get our formula for yield in function of forest distance. In Section 4 we shall compute the parameters α and β using the estimates of Klein et al. (2003c) as a starting point.

We let $\mathcal{A}$ be the coordinates of the total region with area A. We assume that the region that is allocated to shade coffee production has the same shape as $\mathcal{A}$. To be specific, the shape of the region in which shade coffee is produced is unchanged but its size may vary as the allocation of area to shade coffee production changes. This assumption makes it possible to do all the calculations in the original coordinates and to obtain the yield by scaling the results with factor μ. Hence, in computing the yield we avoid defining the location of the shade-coffee region over which we should compute the yield. In this section the shape of the region is arbitrary. In Section 4 we shall make computations assuming a circular shaped region.

The pollinator source is the forest strip that surrounds the shade coffee plantation. In practice, the forest patches could be located in more complex way depending on the landscape. Olschewski et al. (2006) have analyzed the economic impacts of bee pollination by assuming that the cultivated region surrounds the forest. We assume that shade-coffee production involves the surrounding forest strip, range of which depends on the area that is allocated to shade-coffee production. To be specific, a portion of land allocated to shade-coffee production is covered by forest. We make a simplifying assumption that the forest strip has a fixed width δ_0 regardless of the size of the area.

From now on we let $\delta(x)$ denote the distance of point x from the border of the whole region allocated to shade coffee, including the forest strip. In other words, $\delta(x) = d(x) + \delta_0$. As the shape of the region is invariant and its area is changed by a factor $\mu \in [0, 1]$, then those points in the original coordinates which satisfy $\delta(x) < \delta_0/\sqrt{\mu}$ belong to the forest strip of the region that is shrinked with factor μ. Moreover, the minimal yield $y_{\min}$ is exceeded at points which satisfy

$$\delta_0/\sqrt{\mu} \leq \delta(x) \leq (\delta_u + \delta_0)/\sqrt{\mu}, \tag{1}$$

where $\delta_u = (\alpha - y_{\min})^2/\beta^2$. Here δ_u is the distance from forest strip above which the yield of a plant is $y_{\min}$, i.e., it is obtained from $y_{\min} = \alpha - \beta\sqrt{\delta_u}$.

By $\mathcal{A}(\mu)$ we denote those coordinates of the whole coordination $\mathcal{A}$ that satisfy (1). Hence, those points in $\mathcal{A}$ that belong to $A(\mu)$ produce coffee after shrinking of the region by factor μ. Then the yield of the shrinked area is obtained by computing the yield of $A(\mu)$ and then scaling it with factor μ. In brief the idea is to compute the yield as if the whole region $\mathcal{A}$ was allocated to shade coffee production and forest and then scaling the resulting yield to the level that corresponds to the shrinked area.

The shrinking of the region and the crucial distances from the the boundary of the region are illustrated in Figure 1. Note that in Figure 1 the area in the right that is between the forest strip (dotted region) and the dotted boundary line is allocated for sun-coffee. In the shaded region the yield per plant is over $y_{\min}$ and in the central area the yield is $y_{\min}$.

The area of the region of $\mathcal{A}$ in which the yield per plant will be $y_{\min}$ after shrinking is denoted by $B(\mu)$ and the area of the region that will be the forest strip after shrinking is denoted by $C(\mu)$. Similarly as the yield, these areas are computed in original coordinates $\mathcal{A}$ which means that they should be scaled with μ to obtain the correct areas after shrinking of the original region. Let $Y_{\min}$ denote the yield per hectare inside the region in which the yield per plant is $y_{\min}$. Hence, the total yield of shade coffee for a region that is obtained from

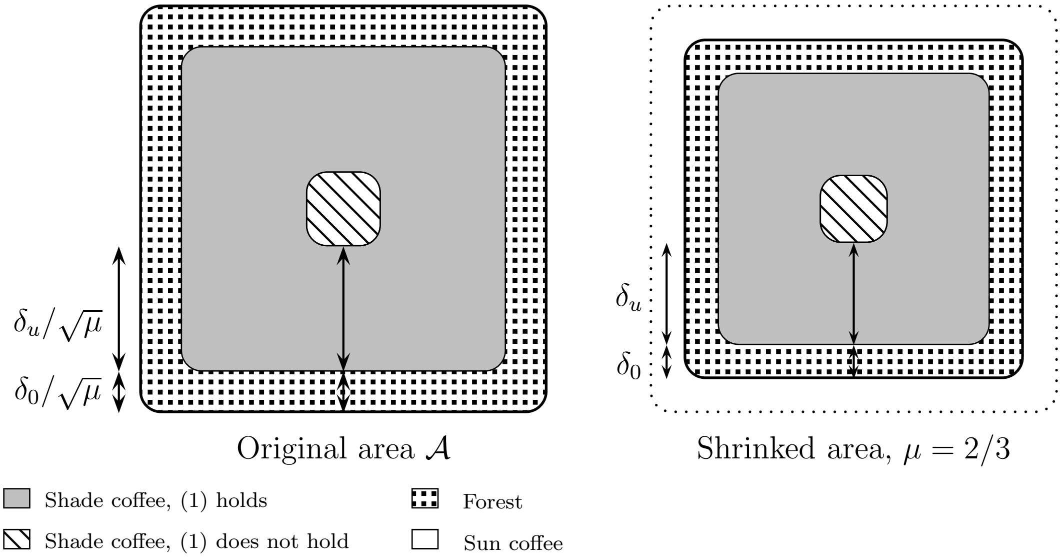

Figure 1. Illustration of shrinking

$\mathcal{A}$ by shrinking it with factor μ is

$$Y_2(\mu;\mathcal{A}) = \mu \int_{\mathcal{A}(\mu)} \left(\alpha - \beta\sqrt{\sqrt{\mu}\delta(x) - \delta_0}\right) dx + \mu B(\mu) Y_{\min}. \tag{2}$$

Remember from earlier that the yield of a plant located at x is $\alpha - \beta\sqrt{d(x)}$ and the fact that $d(x) = \delta(x) - \delta_0$. The factor $\sqrt{\mu}$ in the integrand scales the integrand so that its maximum is α and minimum is $y_{\min}$. The multiplier μ outside the integral scales the result to the level that corresponds to the shrinked area. Recall that $\mathcal{A}(\mu)$ over which the integral is computed is a subset of the original coordinates $\mathcal{A}$ and therefore the resulting integral should be scaled with μ.

The total profit of shade coffee is obtained by subtracting the costs from net profits and adding the profits from the forest strip:

$$\pi_2(\mu) = (p_2 - c_2) Y_2(\mu;\mathcal{A}) - e_2\mu[A - C(\mu)] + p_3\mu C(\mu), \tag{3}$$

where p_2 is the shade-coffee producer price, c_2 is the yield proportional cost factor, e_2 is the area proportional cost factor, and p_3 is the per hectare price obtained from the forest strip. This price may represent for instance the protection fee. In Section 4.2 we shall study p_3 as a policy instrument. Initially p_3 is set to zero. Since the forest strip does not cause any costs we subtract $C(\mu)$ from the total area in the second term of the sum in (3). The above profit function does not account for the possible extra profits that are obtained from the products of shade trees. These may include for instance medicines, foods, construction materials and forage (Moguel and Toledo, 1999).[4]

3.2 Equilibrium and Joint Profits Maximum

We study two different farm structures: *sole owner* and small scale farms. In the former setting the land allocation decision between shade and sun coffee is made by maximizing total profits of the two technologies, i.e., by solving the optimization problem $\max \pi_1(\mu) + \pi_2(\mu)$. In the latter setting, we assume that there is no coordination but a large number of small-scale farmers can decide between belonging to sun-coffee or shade-coffee farmers.

The sole owner that maximizes the joint profits of the technologies will choose to allocate the land to either of the two technologies or take the allocation that satisfies the first order optimality condition $d\pi_1(\mu)/d\mu + d\pi_2(\mu)/d\mu = 0$ which can be written as

$$d\pi_2(\mu)/d\mu = A[(p_1 - c_1)Y_1 - e_1]. \tag{4}$$

Geometrically this condition means that the optimum is at the point where π_2 has a tangential line with slope $A[(p_1 - c_1)Y_1 - e_1]$. This is illustrated in Figure 2 where the dotted line is the tangent of π_2 at joint profits maximum.

Let us now discuss the small scale farm setting, where each farm decides to which of the two technologies to allocate the land. We assume that there are many farmers so that each farmer's marginal contribution to the profitability of the technology is negligible. The total profits from the technologies are shared in proportion to farm sizes. Thus, for a farmer whose land covers an area Δ of the region the profits from sun-coffee production would be $\Delta \times \pi_1(\mu)/[(1-\mu)A]$ and from shade-coffee production $\Delta \times \pi_2(\mu)/(\mu A)$. This means that the farmers' land allocation choices between the two technologies depend on the profitabilities of the technologies. Notice that in this model an individual farmer has to choose between the technologies and cannot allocate land to both sun-coffee and shade-coffee. In practice this means that the costs of having two production methods are prohibitively large for a small producer. Hence, an individual farmer faces a technology choice problem rather than a land allocation problem.

Since the farmers choose their production technologies on the basis of profitability, the equilibrium is obtained when the profitabilities are the same.

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[4] We are not aware of explicit economic analyses being conducted on the value of coffee plantation shade tree products. In the case of cocoa plantations a brief discussion is provided by Rice and Greenberg (2000). If data were available, inclusion of such impacts in the analysis would present no difficulties.

Namely, if one of the technologies is more profitable, then at least some of the farmers would be willing change the technology. The profitability is measured as profits per hectare and the profitability factors are $\theta_1 = \pi_1/[(1-\mu)A] = (p_1 - c_1)Y_1 - e_1$ and $\theta_2 = \pi_2/(\mu A)$. At the equilibrium none of the farmers has an incentive to change the choice of the technology which means that $\theta_2 = \theta_1$. This condition can be written as

$$\pi_2(\mu) = \mu A[(p_1 - c_1)Y_1 - e_1] \tag{5}$$

and we shall refer to the right hand side line of this condition, the line $\pi = \mu A[(p_1 - c_1)Y_1 - e_1]$, $\mu \in [0, 1]$, as the "reference profits" line because it gives the profit from sun coffee production if a proportion μ of land area were allocated to shade-coffee instead. Note that the slope of the reference profits line is the same as the right hand side of (4).

Let us first focus on the properties of the profit function of shade-coffee production, π_2. For a small enough μ, the corresponding profit $\pi_2(\mu)$ is zero because the whole area is covered by the forest strip; recall the assumption on the fixed width of the forest strip. Note that in equation (1) the lower bound for the distance between a plant and the border of the region increases as μ decreases, which means that below a certain threshold level for μ there are no points that satisfy (1). The interpretation is that the whole region that is outside of sun-coffee production is covered by the forest. After this threshold level π_2 starts to increase.

Depending on the parameter values, the marginal profit is decreasing for large enough μ's. The decreasing marginal profits follow from the fact that the proportion of the area in which the yield is $y_{\min}$ increases and the proportion of the area in which the pollination is effective decreases. Hence, as μ increases, larger portion of the yield comes from the area which is far from the forest. In particular, larger portion is produced in the region in which the yield per plant is $y_{\min}$. However, when shade-coffee production is extremely profitable it may happen that the marginal profit is increasing on the whole interval $(0, 1)$ after the point in which π_2 becomes positive. Otherwise, there is a point after which the marginal profit is decreasing. If this is the case then π_2 is unimodal for μ over the threshold level after which it becomes positive. This means that π_2 is increasing until it reaches its maximum and then starts to decrease. An example of such a profit function is illustrated in Figure 2 where the reference profits line is also presented as the dashed line.

As seen in Figure 2, π_2 crosses the reference profits line twice. Hence, there are two equilibria; μ_u and μ_s in the figure. On the interval (μ_u, μ_s) the profit function π_2 is above the reference profits line, which means that the profitability of shade coffee is greater than the profitability of sun-coffee, i.e., $\theta_2 > \theta_1$. If we assume that the farmers allocate their land to the technology that is the most profitable, then there is a tendency to move towards the equilibrium μ_s when

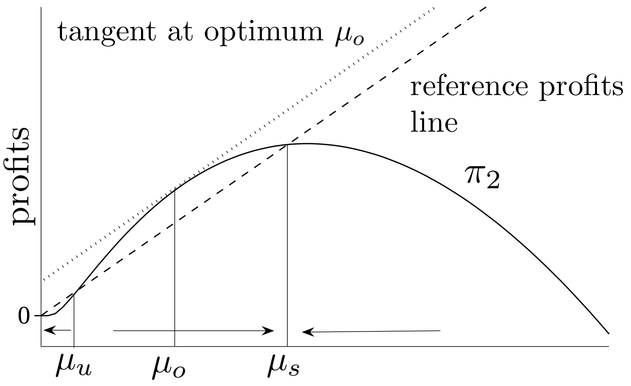

Figure 2. Illustration of π_2, the optimality and equilibrium conditions

starting from an allocation corresponding to a situation where μ belongs to the interval (μ_u, μ_s). For $\mu > \mu_s$ there is also a tendency to move towards μ_s as sun-coffee is more profitable technology and the farmers shift from producing shade coffee to producing sun-coffee and hence reducing μ. Thus, we can say that μ_s is a stable equilibrium. The other equilibrium μ_u is unstable by similar reasoning. We collect these observations to the remark below.

Remark 1. *There are at most two equilibria on interval* $(0, 1)$.

1. *If there are two equilibria* $\mu_u < \mu_s$ *then* μ_s *is stable and* μ_u *is unstable.*
2. *If the equilibrium* μ^* *is unique in* $(0, 1)$*, it is unstable.*
3. *If there are no equilibria in* $(0, 1)$ *then shade-coffee production cannot be more profitable than sun-coffee production.*

If there is a unique equilibrium on $(0, 1)$-interval, then π_2 goes below the reference profits line and touches it at one point, i.e., sun coffee is more profitable than shade-coffee except for that point. Hence, when starting from μ below the equilibrium the farmers would decrease the land allocated to shade coffee. Therefore, this equilibrium is unstable. At the corners $\mu = 0$ or $\mu = 1$ one of the profitability factors cannot be defined. However, when π_2 goes below the reference profits line we can say that there is no shade coffee at equilibrium since its production can never be more profitable than the production of sun coffee. Whenever there is a forest strip surrounding the shade coffee plantation, it is not possible that π_2 goes above the reference profits line for all $\mu \in (0, 1)$ because due to the forest strip there is always an interval of μ where π_2 is zero. This leads us to our third observation in Remark 1. Recall that throughout this section we assume that $p_3 = 0$.

We can notice that when keeping the other parameters at their original levels and changing only one of them, the equilibrium allocation μ, either stable and unstable one, is increasing in p_2, p_3, c_1, and e_1, and decreasing in c_2, e_2, and p_1. In particular, parameters p_2, p_3, c_1, and e_1 have lower bounds above which there is shade-coffee production in equilibrium. Similarly, c_2, e_2, and p_1 have upper bounds below which there is shade-coffee production in equilibrium. When one of the parameters p_2, p_3, e_1, or c_1 becomes large enough, there is only one equilibrium on interval $(0, 1)$. This is because the stable equilibrium with higher allocation for shade coffee converges to $\mu = 1$ as shade-coffee production comes more profitable.

An example of a stable equilibrium as a function of p_2 is presented in Figure 3, where we see that below a certain threshold (the first dotted vertical line) there are no equilibria on interval $(0, 1)$ and hence all the area is allocated to sun coffee; see Remark 1. Above the other threshold level (the second dotted vertical line) the stable equilibrium coincides with $\mu = 1$ and all the area is allocated to shade coffee. Between these two lines coexistence of the production methods occurs. The unstable equilibria as well as the joint profits maxima are presented in the figure. At the lower threshold level when the shade-coffee production becomes profitable the two equilibria and the joint profits maximum coincide, i.e., there is a unique equilibrium which equals the joint profits optimum. This happens because there is only one equilibrium and at this point the line $\pi = \mu A[(p_1 - c_1)y_1 - e_1]$, $\mu \in (0, 1)$, is tangential to π_2, see equations (4) and (5).

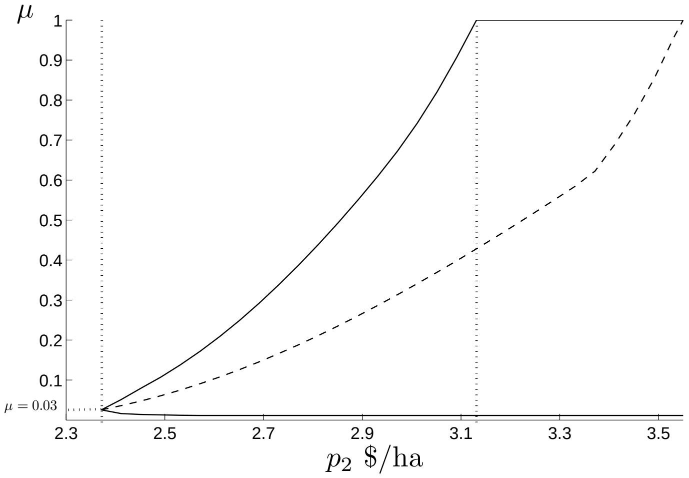

Figure 3. Illustration of equilibria and joint profits optimum (dashed line) as a function of p_2

In addition to stability, another way to select among the equilibria is the dominance. We say that an equilibrium is dominant if the total profits $\pi_1 + \pi_2$ obtain their maximum among all the equilibria at this equilibrium. We can make the following observations on the dominance assuming that the extreme allocations $\mu = 0$ and $\mu = 1$ are equilibria. Indeed, when no land is allocated to one of the technologies, then its profitability is zero and there is no incentive to allocate any land to it.

Remark 2. *Let us consider $\mu = 0$ and $\mu = 1$ as possible equilibria.*

1. *When there are two equilibria $\mu_u < \mu_s$ on $(0, 1)$, then μ_s is the dominant*

equilibrium.

2. *When the equilibrium is unique on* $(0,1)$ *and* π_2 *crosses the reference profits line, then* $\mu = 1$ *is the dominant equilibrium.*
3. *If* π_2 *is below the the reference profits line, then* $\mu = 0$ *is the dominant equilibrium.*

The first part of Remark 2 holds because at μ_s the profits of shade-coffee production are always higher than at μ_u. In the second case, the highest total profits are obtained by allocating all the land to shade-coffee production. In the third case, the total profits are highest when the land is allocated to sun-coffee production. From remarks 1 and 2 we can note that when there are two equilibria on interval $(0,1)$ then the higher of these is both stable and dominant. Therefore, in the following section we shall concentrate on the higher equilibrium whenever there are two equilibria.

Finally, let us compare the dominant equilibrium with the joint profits $\pi_1 + \pi_2$ maximizing outcome obtained with sole ownership. In Figure 2 the profit maximizing point is where the line with slope $A[(p_1 - c_1)Y_1 - e_1]$ (the dotted line) is tangential to π_2. As stated in the following remark, this point can never be above the dominant equilibrium which means that there will be more shade-coffee production in the equilibrium than what would be optimal under sole ownership.

Remark 3. *The maximizer of* $\pi_1 + \pi_2$ *does not exceed the dominant equilibrium allocation.*

If the dominant equilibrium is at $\mu = 0$ so is the maximizer of total profits as Remark 3 says. When the dominant equilibrium is obtained at $\mu = 1$, the maximizer can be at most at this point. Whenever, the dominant (and stable) equilibrium μ_s is obtained on $(0,1)$, it is obtained at a point in which the marginal profits are decreasing, i.e., π_2 curve goes above the reference profits line on $[\mu_u, \mu_s]$, where μ_u is the dominated (and unstable) equilibrium. Assuming that π_2 is continuously differentiable on $[\mu_u, \mu_s]$ we get from the intermediate value theorem that there is a point on interval $[\mu_u, \mu_s]$ at which the tangent of π_2 has the slope $A[(p_1 - c_1)Y_1 - e_1]$. At this point the first order condition (4) is satisfied and hence the maximizer is at most μ_s.

Since our model involves rather complex yield function (2), it is difficult to solve the equilibrium and joint profits maximum analytically even when assuming that the shape of the region is simple, e.g., circular. In the following section, we shall analyze the model numerically to obtain more insight on its properties.

4 Empirical Application

We apply the analytic model constructed in the previous section to the specific case of production of shade and sun coffee in Costa Rica. The main objectives are: *i*) to assess whether coexistence of both production types is possible, given the model specification used; *ii*) to assess to what extent the parameters used would need to be changed for a corner solution (of either sun or shade coffee); and *iii*) to assess the relative impacts of alternative policy instruments.

The issue is important not only from the point of view of sustainable coffee production but also from forest conservation perspective. Deforestation is a particular environmental problem in the northern Latin American region. *C. arabica* is grown in mid elevation mountain ranges and volcanic slopes where deforestation has been particularly severe. In some areas, shade coffee production areas are among the few remaining forested areas (Perfecto et al., 2005).

Further, coffee is an important product for this region. Commercial coffee production in Costa Rica began in 1832 and until 1900 produced virtually all of the country's foreign exchange. It has been one of most important factors in economic development of Costa Rica and still is a major source of employment in rural areas. 17.8 million man-days were directly created by coffee production in 1995–96, translating to employment for 4.9% of total work-force. 14% of gross value of agricultural production came from coffee in 1996 (Agne, 2000).

ICAFE, the national coffee institute, controls all Costa Rican exports and sales by, for instance, fixing an annual export quota. In 1995–96 about 90% of the coffee yield was exported, most of which to the European Union. Profits to exporters and processors are set by government regulation, and hence it is the producers who bear all the price risk. In addition, the producers receive their revenue in small and variable portions along the year. As a result, the producers do not know the price when they make input use decisions, nor actually do they know it when they deliver the product. (Agne, 2000)

Costa Rica produces *C. arabica* as the production of *C. robusta* is prohibited by law (ICAFE website, 2006). Central Valley is the most important production area, and it has been estimated that sun coffee is the predominant production method in Central Valley, whereas in the surrounding areas shade-coffee production takes place (Agne, 2000). We concentrate on bees as the providers of the pollination service, as they are an important pollinator of both highland and lowland coffee. Important pollinators of Costa Rican coffee flowers include the non-native feral African honeybees (*Apis mellifera*) and 10 native species of stingless bees. (Klein et al., 2003a, Kremen et al., 2002, Ricketts et al., 2004, Roubik, 2002)

The shade trees in Costa Rica have been argued to be fairly young and thus do not provide cavities preferred for nesting sites by common coffee-pollinating bees. Hence the decisive matter for pollination is the distance to the nearest forest, not the shade trees (Ricketts et al., 2004).

We abstract from the further specifics of Costa Rican circumstances in order to concentrate on demonstrating the economic impact of forest distance and cross pollination to coffee production. Data for an empirical study are not easy to obtain, but with more accurate data the specifics could be accounted for. We have chosen Costa Rica as the country of interest partly for reasons of data availability. However, certain ecological relationships have been taken from studies conducted elsewhere. Hence, rather than providing exact figures, the purpose of this empirical application is to extract some stylized results from our model with realistic parameter values.

4.1 Parameters

In this section, we present the parameters of our empirical analysis. First, we derive a relationship between yield and distance to a forest strip, or parameters α and β of Section 3.1. Klein et al. (2003c) have presented the regression model below for the fruit-set percentage of *C. canephora*[5]:

$$s = a - b\sqrt{d}, \tag{6}$$

where s is the fruit-set percentage of a coffee plant and d is its distance to pollinator source, i.e., the distance to forest. They have also estimated the parameters such that $a = 94.11$ and $b = 1.15$. Similar regression model for the forest distance and berry weight has been considered by Olschewski et al. (2006). Let us assume that the yield of a coffee plant depends linearly on fruit set percentage s, i.e., $y = \bar{a}+\bar{b}s$ [6]. The two unknowns $\bar{a}$ and $\bar{b}$ can be solved by taking two observations (y_n, s_n) and (y_f, s_f), near and far from the pollinator source, respectively.

According to Ricketts et al. (2004), the average yield for *C. arabica* is $\tilde{y}_n = 21.5$ fa/ha within the region that is inside the range of one kilometer from the pollinator source. One fanegas (fa) amounts to 255 kg of fresh coffee and 46

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[5] Although the relationship is for *C. canephora*, and we deal with *C. arabica*, we justify the decision to use the relationship by the fact that we are not aware of such a relationship being readily available for *C. arabica*. Moreover, Olschewski et al. (2006) reason that the ecological mechanisms for coffee pollination services and coffee berry borer infestation are similar in different regions.

[6] In addition to fruit set, effective pollination enhances fruit mass Ricketts et al. (2004). We do not consider the effect of forest distance to fruit mass.

kg of green coffee; see Lyngbæk et al. (2001). Farther than one kilometer range the average yield is $\tilde{y}_f = 17.8$ fa/ha. Assuming that there are 1500 coffee plants in one hectare, see Rice and Ward (1996), we get the estimates y_n and y_f given in Table 1. We assume that y_n is the yield of a plant in the distance $d_n = 500$ m and y_f is the yield in the distance $d_f = 1,000$ m. In the experiments of Ricketts et al. (2004), the pollination services of bees farther than $1,400$ m from the forest were inadequate. Furthermore Ricketts (2004) observes that plants farther than 300 m from forest rely almost exclusively on pollination of *Apis mellifera*. The fruit set percentages s_n and s_f corresponding to the two distances d_n and d_f can be computed from (6). The values of parameters $\bar{a}$ and $\bar{b}$ are then

$$\bar{a} = (s_f y_n - s_n y_f)/(s_f - s_n) \text{ and } \bar{b} = (y_f - y_n)/(s_f - s_n). \tag{7}$$

The next step is to construct the yield as a function of distance from the pollinator source. From Klein et al. (2003c) and our assumption on a linear relationship between yield and fruit set (see the discussion in Section 3.1) we get $y = \tilde{\alpha} - \tilde{\beta}\sqrt{d}$, where

$$\tilde{\alpha} = \bar{a} + \bar{b}a \text{ and } \tilde{\beta} = b\bar{b}. \tag{8}$$

The above yield model is for a coffee plant, whereas we are interested in getting the parameters for infinitesimal pieces of land over which we integrate to obtain the yield. Hence, we need to calibrate our model such that function (2) produces a realistic yield. The calibration can be done by scaling $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ so that the area of 1065 ha ($A(1) + B(1)$ in (2) for $\mu = 1$) produces $20 \times 1,065$ fa, see Ricketts et al. (2004) who have estimated that 20 fa/ha is the mean yield of their case farm. By taking $Y_{\min} = 12$ fa/ha as the minimum yield for the region far from the forest, we get the scaling factor $\rho = 0.124$. The final parameters are then obtained by multiplying $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\min}$ by this factor, i.e., the parameters α, β, and $y_{\min}$ appearing in Section 3.1 are $\alpha = \rho\tilde{\alpha}$, $\beta = \rho\tilde{\beta}$, and $y_{\min} = \rho\tilde{y}_{\min}$.

Our total circular production area corresponding to the case of Ricketts et al. (2004) is $1,256$ ha, which is the sum of $1,065$ ha and the area of the most significant forest patches surrounding the cultivated region. These forest patches cover 191 ha. The yield parameters are summarized in Table 1.

The cost parameters are not for any specific farm or region but rather they are assumed to be in the same scale as the costs in Table 6 of Kilian et al. (2004) for Costa Rican case farms. The price and cost parameters are presented in Table 2.

Table 1
Yield Parameters

Symbol	Value	Parameter	Source
A	1,256 ha	The total circular production area including forest	Ricketts et al. (2004)
Y_1	41 fa/ha	Yield of sun coffee	Kilian et al. (2004)
a	94.11 %	Intersect in equation determining shade coffee fruit set as a function of forest distance	Klein et al. (2003c)
b	1.15	Distance coefficient in equation determining shade coffee fruit set as a function of forest distance	Klein et al. (2003c)
y_n	$0.0143\ \frac{\text{fa}}{\text{plant}}$	Yield of shade coffee close to forest (<1km)	Kilian et al. (2004)
y_f	$0.0119\ \frac{\text{fa}}{\text{plant}}$	Yield of shade coffee far from the forest (>1km)	Kilian et al. (2004)
s_n	65 %	Fruit set percentage close to forest	Obtained from (6)
s_f	58 %	Fruit set percentage close far from the forest	Obtained from (6)
$\bar{a}$	-0.016	Intersect in equation determining shade coffee yield as a function of fruit set percentage	Obtained from (7)
$\bar{b}$	4.8×10^{-4}	Yield coefficient in equation determining shade coffee yield as a function of fruit-set percentage	Obtained from (7)
$\tilde{\alpha}$	$0.0285\ \frac{\text{fa}}{\text{plant}}$	Intersect in equation determining shade coffee yield as a function of forest distance	Obtained from (8)
$\tilde{\beta}$	5.48×10^{-4}	Distance coefficient in equation determining shade coffee yield as a function of forest distance	Obtained from (8)
$\tilde{y}_{\text{min}}$	$0.008\ \frac{\text{fa}}{\text{plant}}$	Minimum yield per plant	Assumption
Y_{min}	12 fa/ha	Minimum yield per hectare	$Y_{\text{min}} = 1,500 \times \tilde{y}_{\text{min}}$
ρ	0.124	Scaling factor for $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{y}_{\text{min}}$ to obtain final values	Obtained from requiring the yield of 1,065 ha region to be 20×1,065 fa
δ_0	158 m	Forest strip width	Obtained by assuming a circular forest strip of 191 ha as in Ricketts et al. (2004)

Table 2
Price and Cost Parameters

Symbol	Value	Parameter	Source
c_1	\$0.50 /kg	Yield dependent costs in sun coffee production	Kilian et al. (2004), Ricketts et al. (2004)
c_2	\$0.50 /kg	Yield dependent costs in shade coffee production	Kilian et al. (2004), Ricketts et al. (2004)
e_1	\$1,650 /ha	Area dependent costs in sun coffee production	Kilian et al. (2004)
e_2	\$2,090 /ha	Area dependent costs in shade coffee production	Agne (2000), Kilian et al. (2004)
p_1	\$1.39 /kg	Producer price of sun coffee	Kilian et al. (2004)
p_2	\$2.98 /kg	Producer price of shade coffee	Kilian et al. (2004)
p_3	\$0 /ha	Protection fee	Assumption

4.2 Results and Policy Implications

In this section we investigate the dominant equilibrium and the joint profits maximum of our empirical case. Our base scenario corresponds to parameter values presented in Tables 1 and 2. For these values the equilibrium is to allocate 69% of the area to shade-coffee production. The optimum that would maximize the total profits from the whole region is to allocate 32% of the area to shade coffee. This means that when the farmers do not coordinate their land allocation decisions, they over-allocate considerably in the more profitable technology that proves to be shade coffee, given our initial parameter values. The result for the base scenario ($\mu = 0.69$) can be compared to to the area that has been estimated to be under shade production in Costa Rica, $\mu = 0.60$ (Dicum and Luttinger, 1999).

The profits from shade coffee at equilibrium are about $24,600 and from sun coffee about $11,200, i.e., the total profits are about $35,800. At the equilibrium, the profitability of the two technologies are the same $28.5 /ha which is also the total profitability. The size of the forest strip corresponding to the equilibrium is 157 ha. At the joint profits maximizing allocation shade coffee pays $86,900 ($217 /ha including the forest strip 105 ha), sun coffee pays $24,400 ($28.5 /ha), and total profits are $111,300 ($88.6 /ha). Hence, the lack of coordination leads to significant losses. On the other hand, there are environmental benefits from having more shade-coffee production than what a profit maximizing optimum would provide.

The profits and profitabilities in small scale farming and sole ownership scenarios are summarized in Table 3. Optimum refers to the the maximum of joint profits from the technologies and equilibrium refers to the dominant equilibrium. Without the forest strip the yield per hectare is much larger in the joint profits optimum due to a lower area being subjected to producing the minimal per hectare yield $Y_{\min}$.

Table 3
Key figures (* yield/ha without the forest strip included)

Technology	Scenario	Allocation (μ)	Profits	Profits/ha	Yield/ha
shade coffee	equilibrium	0.69	$24,600	$28.5 /ha	700 kg/ha (856 kg/ha)*
sun coffee	equilibrium	0.31	$11,200	$28.5 /ha	Y_1 (1,886 kg/ha)
shade coffee	optimum	0.32	$86,900	$217 /ha	710 kg/ha (960 kg/ha)*
sun coffee	optimum	0.68	$24,400	$28.5 /ha	Y_1

As the results in the base scenario may be driven by the initial parameter values, we also compute a minimum price that would guarantee production of shade-coffee. The threshold for the price p_2 below which there is no shade-coffee production at equilibrium is about $2.35/kg. In other words, the price margin $p_2 - p_1$ should be at least $0.96/kg. The threshold for p_2 above which there is only shade coffee in dominant equilibrium is about \$3.13/kg, i.e., $p_2 - p_1$ should be at least \$1.74/kg. The upper and lower thresholds are illustrated as dotted vertical lines in Figure 3, where the equilibrium as well as joint profits maximum are illustrated as a function of p_2. From these threshold levels we obtain also threshold levels for the cost c_2 and the cost margin $c_2 - c_1$. The cost c_2 should not increase above \$1.15/kg, i.e., the cost margin should not exceed \$0.65/ha while prices stay at their initial levels (Table 2). The upper threshold for joint profits maximum is \$3.55/kg. Recall from Section 3.2 that the lower thresholds are the same for equilibria and the joint profits maximum because when the shade-coffee production becomes profitable there is only one equilibrium and this equilibrium is also the joint profit maximizer.

It is clear that the increase of protection fee (p_3) increases the shade-coffee production both in equilibrium and in the joint profits maximum. For an increase of \$100 in p_3, the allocation of shade coffee in the equilibrium increases about 4.47% whereas the allocation in joint profits maximum would increase about 1.25%; see the left part of Figure 4. Small scale farming is thus more sensitive to protection fee. This is because shade-coffee plays a more important role in the dominant equilibrium (small-scale farming) than in the joint optimum (sole ownership). The portion of shade coffee in joint optimum increases only slowly as a function of protection fee because profits from shade coffee are decreasing for $\mu \geq 0.34$ and they are negative for $\mu > 0.76$. Therefore, protection fee is a rather inefficient instrument under sole ownership.

According to Ricketts et al. (2004) that the Costa Rican Environmental Service Payments Program would pay \$42/ha for the conservation of the forests within their study area. If we relate this amount to the data in the left part of Figure 4, we see that the impact of such an amount at the larger level is negligible (there would be changes of only few percentage points in the shade coffee area). Naturally, if we value the forests for benefits other than the pollination service, such a payment may be warranted, but it is worth noting that according to our analysis it would not be sufficient to alter the profitability relations of sun and shade coffee in any significant way.

From Table 6 of Kilian et al. (2004) we can estimate that 29% of the area proportional cost, e_2, are labor costs. For a corresponding cost of sun-coffee, e_1, the percentage is 27%. In Costa Rica the state sets minimum wages, and in 2003 the monthly minimum wage was \$142 (U.S. Department of State, Bureau of Democracy, Human Rights, and Labor, 2004) which we assume to be the minimum wage for farm workers.[7] Assuming that the labor costs are only due

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[7] Note that the highest minimum wage in Costa Rica is for university graduates, \$560 per month. According to an ILO database, non-qualified workers in the agricultural sector received about \$9.1 per day, or about \$182 per month at maximum in 2003.

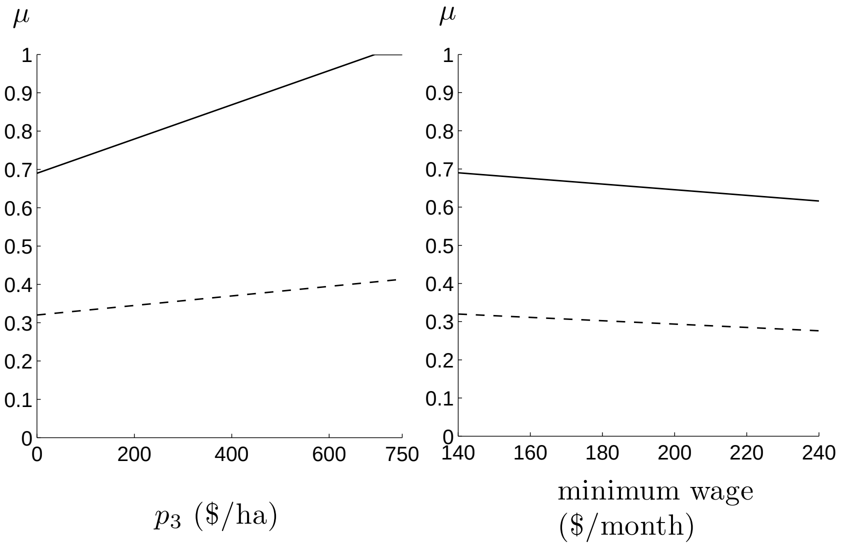

Figure 4. Equilibrium and joint profits optimum (dashed lines) as functions of p_3 and minimum wage

to wages, we have that shade coffee requires 4.27 person months of labor per hectare and sun coffee requires 3.14 person months. Now we can analyze the effect of minimum wages on the equilibrium allocation of land. Since shade-coffee production is more labor intensive, the amount of land allocated to it decreases as the minimum wage is increased.

A minimum wage increase of $100 (71%), i.e., from $142 to $242, would decrease the proportion of shade-coffee land about 14% in the joint optimum (under sole ownership) and about 10% in the dominant equilibrium (no coordination, small-scale farming). The change is illustrated on the right in Figure 4. In Figure 5, the left part illustrates the price of shade coffee that is required to maintain the equilibrium and joint profits optimum at the initial levels when the minimum wage increases from $142 /month. On the right in Figure 5, we see the required protection fee for keeping the land allocations in their original levels as the minimum wage increases. For an increase of $100 in minimum wage the protection fee to compensate the effect of raised minimum wage is about $193 /ha for the dominant equilibrium (small-scale farming) and about $376 /ha for the joint optimum (sole ownership), which are reasonably high figures. It should also be noted from Figure 5 that corresponding increases required for price premium would be $0.05/kg, or 1.7% for the dominant equilibrium and $0.07/kg, or 2.3% for the joint optimum. These comparisons suggest that the importance of a choice of a policy instrument should not be underestimated.

Therefore, Table 4 summarizes the impacts of alternative policy instruments on the proportion of shade-coffee production, μ, and forest area. Given that a donator would spend $50 per hectare to the total area (or $\$50/\text{ha} \times 1,256\text{ha} =$

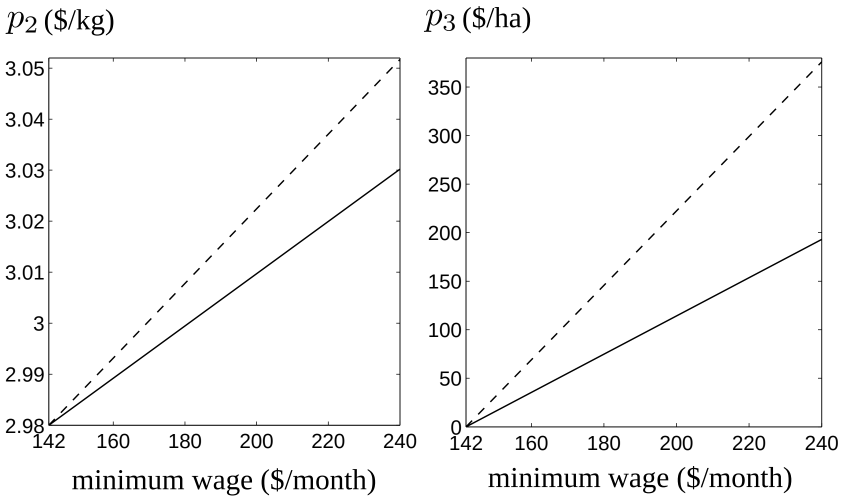

Figure 5. Shade-coffee price and protection fee for equilibrium and joint profits optimum (dashed lines)

Table 4
Comparison of policy impacts when an additional payment of $50/ha is delivered to farmers through alternative policy instruments

Instrument	Scenario	Value (change)	Shade coffee μ (change)	Forest area (change)
minimum wage	equilibrium	$156 /month (+10%)	0.68 (−1.5%)	156 ha (−0.6%)
	optimum	$157 /month (+11%)	0.31 (−2.1%)	103 ha (−1.1%)
protection fee (p_3)	equilibrium	$358 /ha	0.85 (+22%)	175 ha (+11%)
	optimum	$542 /ha	0.39 (+21%)	116 ha (+11%)
price premium ($p_2 - p_1$)	equilibrium	$1.69 /kg (+6.4%)	0.89 (+29%)	179 ha (+14%)
	optimum	$1.72 /kg (+8.4%)	0.41 (+29%)	120 ha (+14%)

$62,800) to preserve biodiversity, the largest increase in shade-coffee production (29%) and forest area (14%) would be achieved by increasing a price premium (by about $0.10, or about 6.5%). In contrast, if the same amount of funding were spent on compensating additional input cost, or an increase in wage level targeted for poor employees, the minimum wage could be increased by 10% with only a negligible negative impact on forest preservation. However, allocating funding through a protection fee would increase both shade-coffee and forest area, but a fee as high as $358 per forest hectare would be required. Assuming that farmers are rational and respond to the alternative instruments accordingly, our results suggest that an effective protection fee should be so high that implementing it might turn out to be difficult. Furthermore, both a price premium and a protection fee increase considerably the gap between the dominant equilibrium and the joint optimum in land use ($21 - 26\%$) contributing to an increased inefficiency.

4.3 Sensitivity Analysis

Here we carry out sensitivity analysis for some essential parameters of our model. We study the effect of the yield of sun coffee (Y_1), the minimum width of the forest strip (δ_0), and the minimum yield of shade coffee ($Y_{\min}$).

As the forest strip surrounding the shade-coffee region becomes wider, the equilibrium allocation as well as joint profits maximum of shade coffee decreases. This is illustrated on the left in Figure 6. When δ_0 exceeds about 430 m, there is no more shade coffee production in the dominant equilibrium or in the joint optimum.

The second parameter for which we carry out sensitivity analysis is the minimum yield $Y_{\min}$. A lower bound for $Y_{\min}$ is obtained by requiring that the minimum yield cannot be obtained at a distance that exceeds the radius of the whole region. This lower bound is 7.6 fa/ha (350 kg/ha). If the minimum yield were below this level, the equilibrium and the joint profits maximum would stay at the same level as when the minimum yield is 7.6 fa/ha. The effect of the choice of $Y_{\min}$ (or $\tilde{y}_{\min}$) to the dominant equilibrium and the joint profits maximum is illustrated in the right part of Figure 6.

As $Y_{\min}$ is changed, the scaling factor needs to be recomputed. Hence, the effect of $Y_{\min}$ may be counterintuitive at the first sight; the shade-coffee allocation decreases although the minimum yield increases. This happens because of rescaling. Intuitively, when $Y_{\min}$ becomes smaller the pollination effect becomes stronger and the equilibrium and the joint profits optimum become higher. When $Y_{\min}$ becomes sufficiently large (about 960 kg/ha), the shade-coffee production becomes more profitable than sun coffee, i.e., there is a jump in the curves of the right part of Figure 6.

Let us now discuss the effect of Y_1. In Figure 7 we have the thresholds for $p_2 - p_1$ below which there is no shade coffee in equilibrium (lower threshold) and above which there is only shade coffee (upper threshold). It is assumed that $Y_1 \geq e_1/(p_1 - c_1) \approx 1,854$ kg/ha (40.3 fa/ha) to guarantee positive profits from sun-coffee production. We can see that the thresholds increase rather slowly as functions of Y_1. The highest Y_1 in the figure, i.e., $Y_1 = 2500$ kg/ha, equals 54.3 fa/ha.

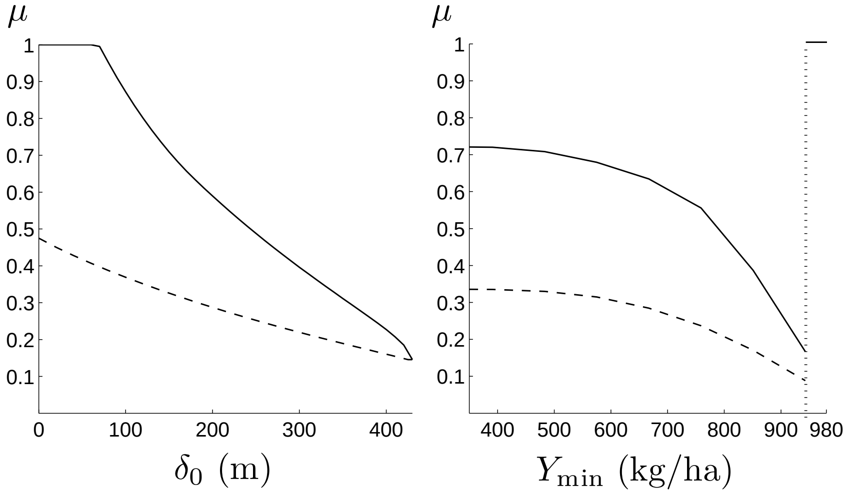

Figure 6. Equilibrium and joint profits optimum (dashed lines) as functions of δ_0 and $Y_{\min}$

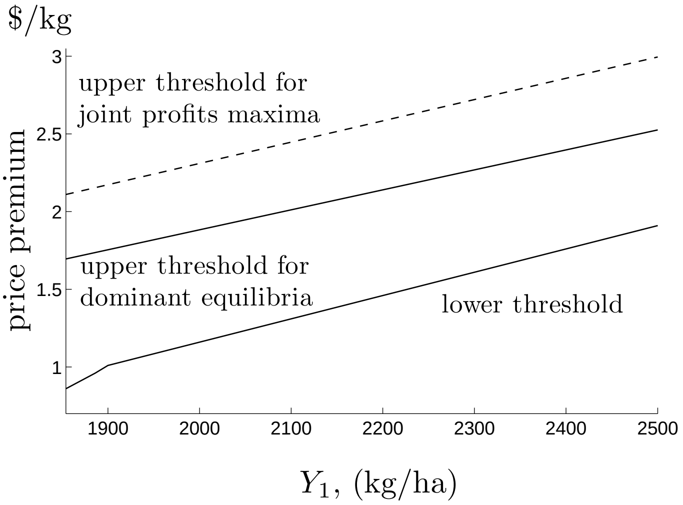

Figure 7. Illustration of critical thresholds of $p_2 - p_1$ for different Y_1

5 Conclusions

Overuse of natural resources may be a direct consequence of poverty. We investigated decline in biodiversity in developing countries using coffee production as an illustrative example. We presented an analytical bio-economic model that captures the interaction between coffee yield and pollination services. Our framework described two alternative “technologies”, sun and shade grown coffee which differ in their ecosystem impacts. Sun grown technology boosts yields by relying on coffee monoculture with high densities and removal of shade trees, nearby forests and their diverse bee habitats which contribute positively to pollinator populations, crucially important for shade-coffee production. Hence, a choice of technology involves a typical trade off between short term private benefits and a public good, biodiversity, or long-term sustainability in land use. We examined the pattern of technology choice and mechanisms that drive the land use process at a representative local community level by calibrating an empirical model using data from Costa Rica.

We found that maintaining environmentally sustainable farming practices requires over-allocation of land to shade-coffee production compared to what would be economically optimal. This inefficiency is inevitable and results from inability to coordinate management decisions when there are several economic agents, typically small-scale farmers, involved. Considerable efficiency losses could be avoided, and costs of preservation could be minimized, by a coordinated management corresponding to management by sole owner. Furthermore, we compared alternative policy instruments - price premiums, protection fees, and minimum wages - and investigated whether it is possible to prevent loss of biodiversity simultaneously with alleviation of poverty. In particular, if production of shade-coffee is more labor intensive, increasing minimum wages would increase the relative profitability in sun-coffee production at the expense of shade-coffee. However, we found this impact negligible in our empirical simulation. Somewhat surprisingly, a direct protection fee turned out to be the most problematic policy instrument as it would increase the cost of preservation in terms of inefficiency by accentuating the over-allocation of technology to shade-coffee production.

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